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Acoustical analysis of an indoor test facility for a 30-mm Gatling gun

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ABSTRACT

The Air Force commissioned a construction and engineering company to build an indoor test facility for the GAU-8 Avenger at Hill Air Force Base in Layton, Utah. The blast pressures from this 30-mm Gatling gun, however, are large enough to cause spallation of the concrete walls over time. The facility is being designed and constructed to last for 20 years, requiring several acoustical treatments. The pressures from the gun were measured outdoors, with maximum pressures exceeding 3000 Pa (163 dB) at a distance of 30 ft (9.1 m). A computer model of the room was designed using EASE, and impulse responses were generated at several positions. These impulse responses were convolved with an ideal blast wave pulse train to mimic the sound of the gun in the room. From these data and results collected from preliminary tests in the range, recommendations have been provided as to placement and types of necessary treatments. Final data confirm that the test facility meets all acoustical and occupational safety requirements.

1. INTRODUCTION

The GAU-8 Avenger, nicknamed the "Tank Killer," is a 30-mm, 7-barrel Gatling gun used on the A-10 "Warthog." The Avenger is capable of firing 4200 rounds per minute with a muzzle velocity of 1066 m/s (more than three times the speed of sound). When a gun is removed from an aircraft for servicing, it must be calibrated and tested before reinstalling it on the plane. However, the high acoustic levels cause a problem. At Hill Air Force Base, personnel have had to make a several-hour round trip to test and calibrate the guns off base at the Utah Test and Training Range (UTTR). In order to improve efficiency, it was desired to build an indoor test range on base for the Avenger and the 20-mm guns used on the F-16, F-22, and AH-1 Cobra helicopter.

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Previously, a similar enclosure had been built to test 20-mm guns on base. However, over time the concrete on the walls of the test bay began to flake from repeated exposure to the high blast pressures. The concept of building an indoor test range for the 30-mm gun was explored in 1985,[1] but it was deemed impractical because measurements suggested pressures near the gun in excess of 90 psi. In addition, exhaust gases would have to be expelled at an extremely fast rate, possibly causing significant noise levels outside of the building. Our goal was to verify or refute those conclusions and provide recommendations for possible acoustical treatments inside and around the test facility.

Because the new building would be required to last for 20 years, the construction company desired to limit the pressures incident on any surface to 3 psi (20 684 Pa). Also, the new structure would also house a machine shop, potentially creating a harmful environment for workers. In order to predict the pressures incident on the walls and in work areas, it was necessary to characterize the noise from the gun. We measured the blast pressures as the gun was fired outdoors at the UTTR and developed a mathematical model of the blast wave. After the designs of the building were complete, a computer model of the room was developed using EASE.[2] Simulation data were compared to experimental data collected in the completed enclosure. Final analysis was conducted to verify that all pressures were under the 3-psi limit and that the test range posed no auditory risks.

2. CHARACTERIZING THE GUN

A. Outdoor Measurements

The tests were conducted at the 30-mm gun range at the Oasis station of the UTTR in November 2007. Data were acquired with National Instruments PXI-4461 and PXI-4462 cards housed in an 18-slot PXI-1045 chassis. The cards permit simultaneous sampling of multiple channels at 204,800 samples per second with 24-bit resolution. The PXI chassis was linked to a Dell laptop via an ExpressCard interface, and the data were streamed to both the internal laptop hard drive and to an external RAID hard drive. A pure sine-wave inverter was used to provide AC power for the data acquisition system in order to eliminate electrical noise often encountered when using a standard modified sine-wave inverter.

Two types of sensors were used for the tests. Within 15 ft (4.6 m) of the gun, piezo-resistive pressure transducers (Dytran and PCB) were mounted on tripods at the same height as the gun (3.5 ft [1.1 m]). Farther from the gun, where pressures were expected to be lower, 1/4" and 1/8" type 1 high-intensity microphones (GRAS) were used and were located at a height of 14 ft (4.1 m). The microphones were located as high as possible to separate the direct and ground-reflected blasts in time as much as possible. A schematic of the composite sensor layout is shown in Fig. 1. The black arrow in the figure denotes the firing direction and 0°, with the positive angle in the counterclockwise direction.

Figure 2 shows the time signal for a single round fired from the Avenger. The initial pulse (0.008 s) in the signal is the sonic boom from the projectile passing the microphone. The largest peak (0.011 s) is the muzzle blast, exceeding 3000 Pa (0.44 psi), and is followed by the ground reflected sonic boom (0.012 s) and the ground-reflected muzzle blast (0.014 s).

The pressures measured at the 30-ft (9.1-m) arc from the gun muzzle show the horizontal directivity of the gun blast. A graph of the peak pressure and root-mean-square (RMS) pressure vs. angle for a 5-round burst is shown in Fig. 3. The maximum pressure actually occurs at 30 degrees off of the firing axis instead of directly in front of the gun because the rapid expansion and contraction of hot gases in front of the gun create a vortex which deflects the sound. This maximum was used as a conservative estimate in considering possible treatments for the range.

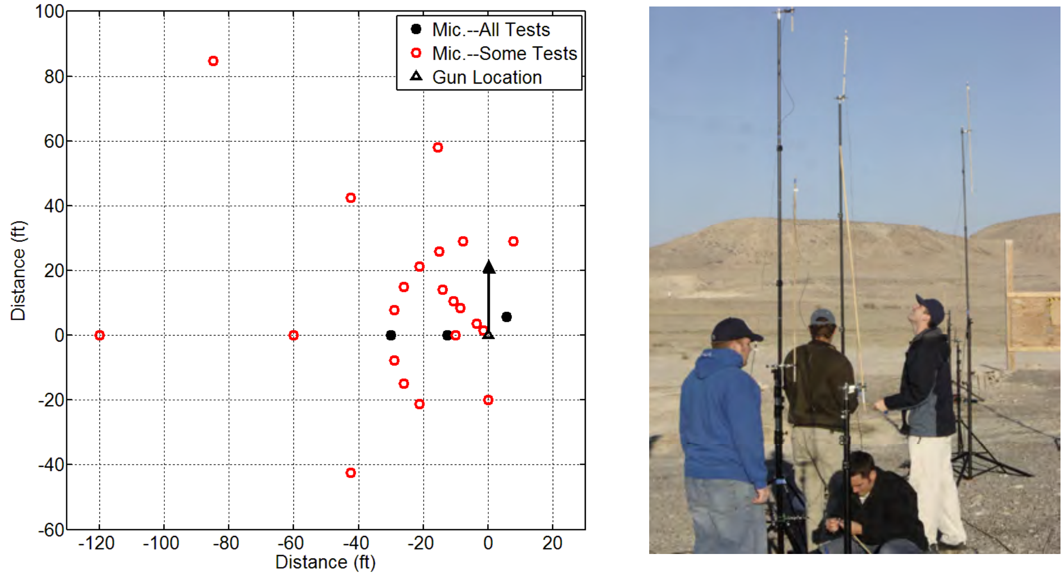

Figure 1: Microphone setup for outdoor measurements.

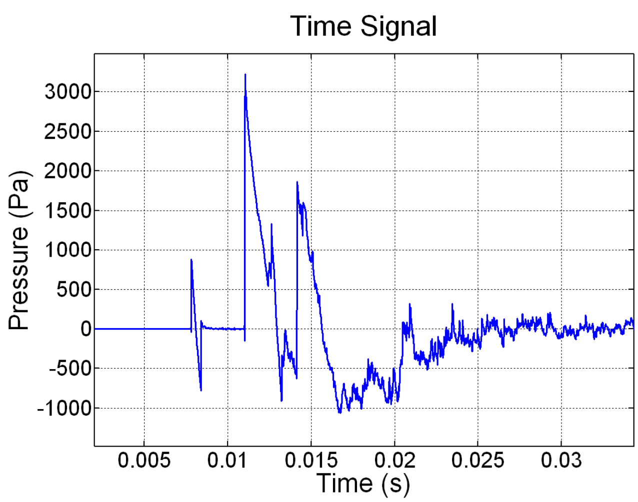

Figure 2: Time signal for single shot, 30 ft away from the muzzle, and 30 degrees off of the firing direction.

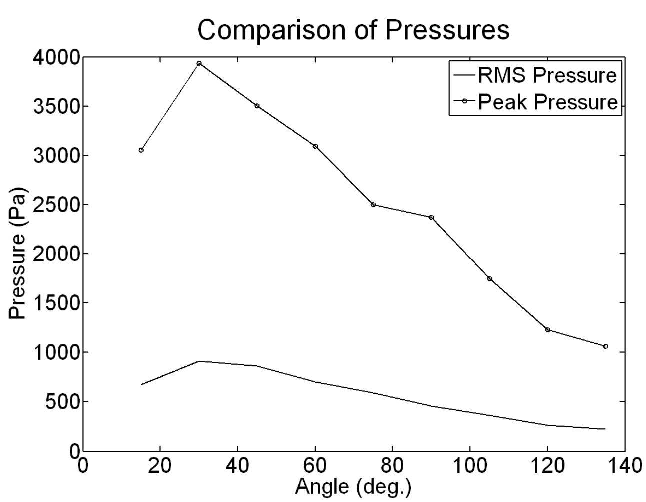

Figure 3: Pressure vs. angle at 30 ft for a 5-round burst.

B. Mathematical Blast Wave

A typical blast waveform can be separated into two main parts: the rise and a damped exponential decay. The rise portion of a weak shock[3] can be modeled as:

$$p(t) = \frac{1}{2} P^+ \{1 + \tanh[(2/t_{rise})t]\}, \tag{1}$$

for $t = 0$ occurring when the pressure is at half of its peak pressure, P^+. The rise time, t_{rise}, describes the change in time of a line that extends from zero pressure to the peak with the same slope as the waveform at $t = 0$. The damped exponential decay is called the modified Friedlander wave equation,[4] given by

$$p(t) = P^+ (1 - t/T^+) e^{-bt/T^+}, \tag{2}$$

and models the expansion of air after an explosion. In Eq. (2), T^+ is the amount of the time the waveform is positive, while the empirical parameter b changes the length of time of the negative portion of the waveform. Using these two equations, an ideal blast wave was created in MATLAB that modeled the waveform in Fig. 2. This blast wave, shown in Fig. 4, was used in convolutions with impulse responses created from the computer model in order to see expected noise levels inside of the room.

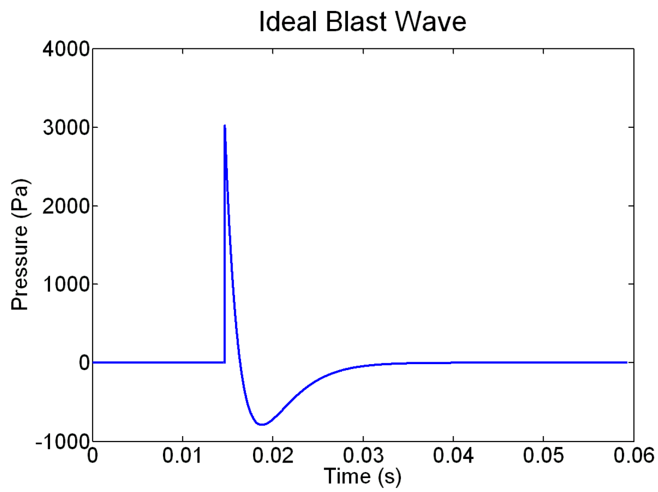

Figure 4: Mathematical model of a blast wave from the gun.

3. COMPUTER MODELING

A. Design

The designs from the construction company were inputted into EASE to create a basic computer model of the indoor test facility. Figure 5 is a screenshot of the model. The large section of the room is 40 ft (12.2 m) wide, 15.3 ft (4.7 m) tall, and 59 ft (18 m) long. A door off the back platform leads to a hallway that connects the entrance to the building to the attached machine shop, and there are two pressure release vents in each back corner. About 20 ft (6.1 m) in front of the gun muzzle, the ceiling drops to 8.5 ft (2.6 m) and the side walls begin to taper. The tunnel tapers from 40 ft wide to 16 ft (4.9 m) over a section about 47 ft (14.3 m) long. 15 ft (4.6 m) beyond the tunnel, the bullets are buried into 60-ft (18.3-m) mound of gravel. At the end of the tunnel is a vent fan that helps circulate the air and expel dust during firing. All of the walls, the ceiling, and the floor in the large section of the room are made of concrete, and most of the floor inside of the tunnel is 6 in (15.2 cm) of gravel.

This design creates several potential acoustical challenges. Nearby faces and intersections, where pressure multiplies because of source imaging, are critical areas. Because of the gun radiation's directionality, the face that drops from the ceiling is exposed to the maximum pressures created by the muzzle blast. Also, the tapered side walls create a sound focusing several yards down the converging tunnel. Lastly, the room vents and exits will potentially transmit high noise levels outside, which could pose an auditory risk for personnel.

The arrow in Fig. 5 points to a speaker that represents the gun muzzle and also denotes the firing direction. The gun was simulated using an omnidirectional speaker with a sound power of 180 dB at 1 m. Impulse responses were generated at each of the locations shown in the figure as listener seats.

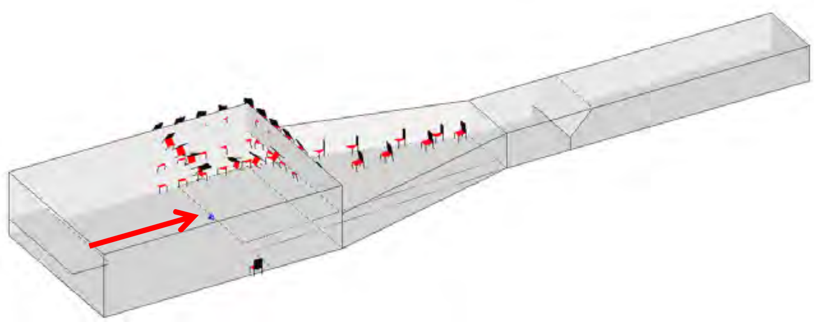

Figure 5: Screenshot of EASE model.

B. Impulse Responses

The following figures are normalized impulse responses generated by EASE. Next to them are convolutions of those impulse responses with a 10-round full-rate pulse train. Figure 6 is of the side wall at gun height. The convolution shows that the initial pulse is multiplied by a factor of four because the direct sound and the ground reflection arrive very close together in time. The next several pulses, however, arrive close to early reflections and total as much as six times the direct sound. Since the side wall is about 20 ft (6.1 m) from the muzzle, this means a possible incident pressure in excess of 24 000 Pa (3.5 psi).

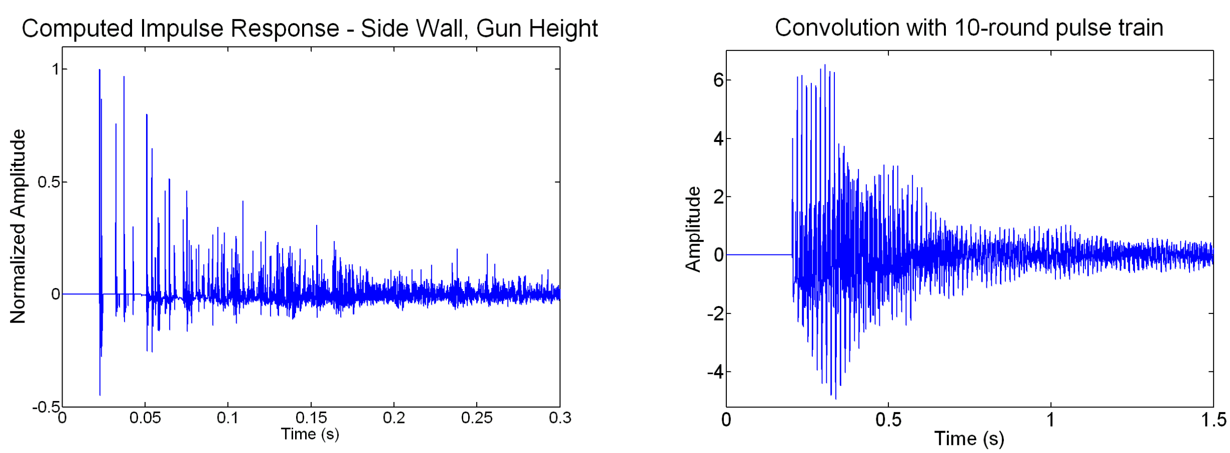

Figure 6: Impulse response and convolution for a position at the firing line, on the side wall, at gun height.

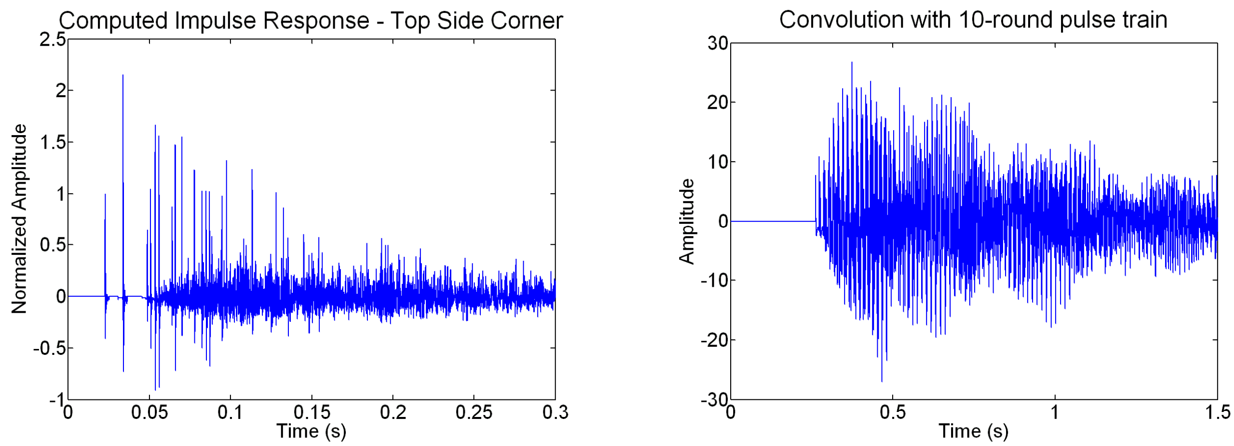

Figure 7: Impulse response and convolution for a position at the top corner.

Figure 7 shows the impulse response and convolution for the interior corner of the ceiling, side wall, and front face. Note that the impulse response shows several early reflections that add up to more than double the initial sound and arrive about the same time as the next muzzle blast. A similar increase occurs as with the side wall, except that the effect is magnified because it is a 3-wall intersection. The convolution shows an octupling of the initial blast, which occurs because of image sources. The corner is about 30.7 ft (9.4 m) away from the muzzle, meaning that the corner could be exposed to pressures above 65 000 Pa (9.4 psi).

Figure 8 is of the ceiling about 35 ft (10.7 m) in the converging tunnel. Note that the early reflections add up to almost three times the direct sound. The convolution shows an increase of a factor of more than twenty, totaling pressures similar to those found in the interior corner.

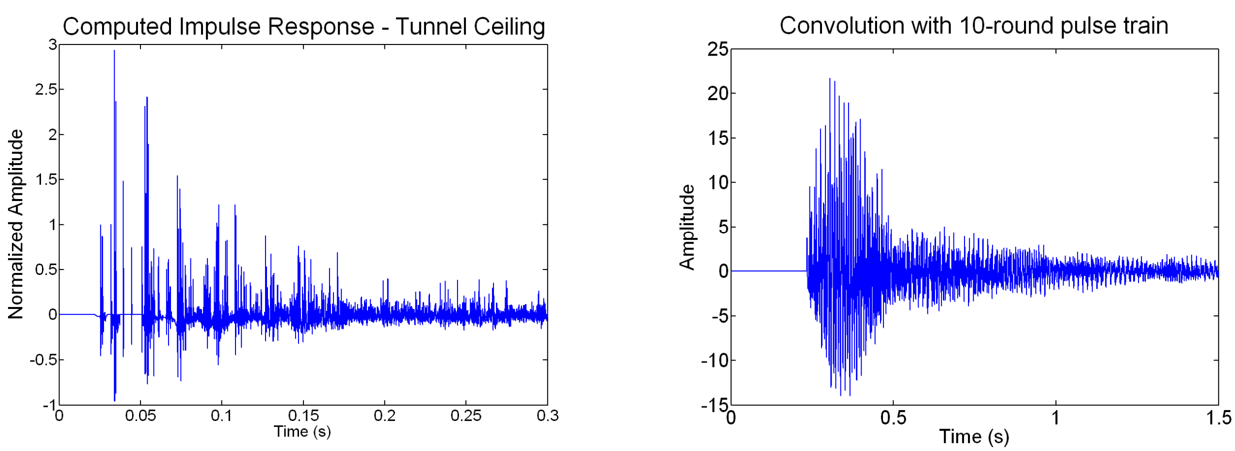

Figure 8: Impulse response and convolution for a position on the ceiling inside the converging tunnel.

In order to attenuate the early reflections and reduce the reverberant energy in the room, six inches of fiberglass insulation was put in the computer model on the walls and ceiling from 5 ft (1.5 m) behind the firing line to 10 ft (3.0 m) inside the tunnel. Figure 9 shows the impulse response and convolution for the same position as Fig. 8 after incorporating the fiberglass into the computer model. Note that the early reflections are attenuated by more than a factor of two in the impulse response and that the convolution is significantly reduced in both peak amplitude and reverberant energy.

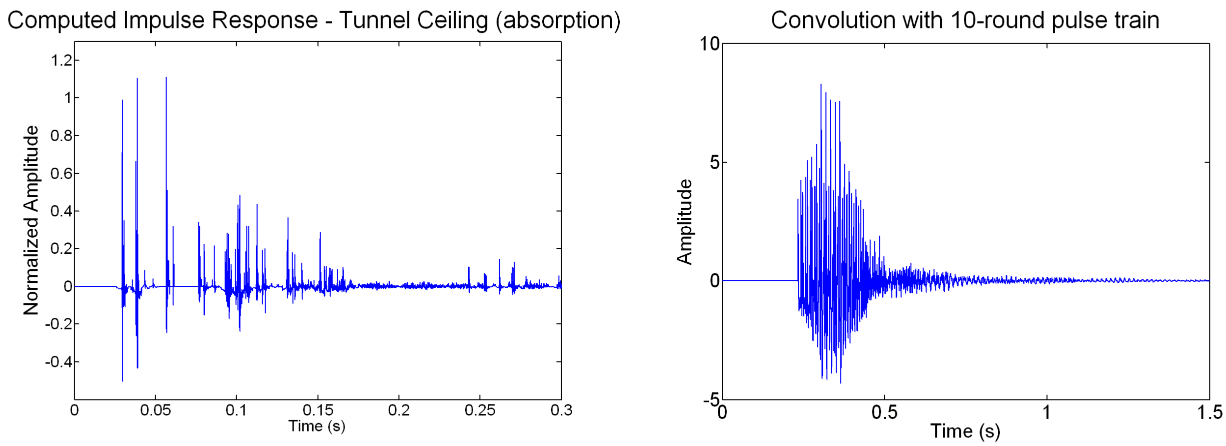

Figure 9: Impulse response and convolution for a position on the ceiling inside the converging tunnel with absorption on the walls and ceiling.

4. INDOOR MEASUREMENTS

A. Concrete Room

After the construction company finished the basic structure, acoustical measurements were taken on the room using the same equipment as for the outdoor measurements. A starter pistol was used as a sound source. Figure 10 shows the response of the room at the two of the locations described above: the side wall and the tunnel ceiling. The measured data show that the room performed much better than expected, probably due to extra scattering from imperfections in the concrete surfaces and gravel floor.

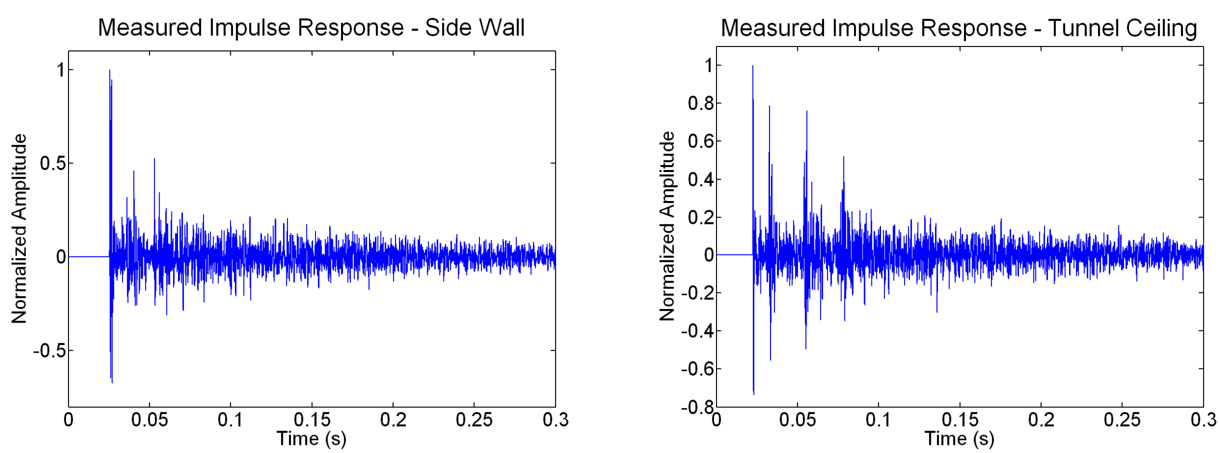

Figure 10: Impulse responses for empty range.

B. Acoustical Treatments

Despite the fact that the reverberant energy in the room was less than was predicted by the model, the direct pressures incident on some surfaces of the room were still high enough to be of concern. This was especially true for locations where the ground reflection arrived nearly simultaneously with the direct sound. Two possible treatments were explored to minimize this problem. As was tested in the computer model, wall and ceiling surfaces could be covered with a dense, absorptive material to reduce incident pressures, reflections, and reverberant energy. While this will not be very effective in for low-frequency noise, it will be effective in attenuating high frequencies, thereby reducing peak pressures. Another possible treatment was an obstruction up close to the gun, some sort of muffler to attenuate the sound close to the source.

For the wall treatments, Rockwool insulation was chosen because it is both absorptive and fire retardant. A simple insertion loss measurement was conducted in an anechoic chamber to find the effectiveness of the Rockwool insulation. The graph in Fig. 11 shows that the peaks were reduced by a factor of about five, implying good high-frequency absorption. During measurements with the 20-mm gun, the reduction factor was between three and four.

The walls and ceiling of the range were covered with 6 in (15.2 cm) of insulation from 5 ft (1.5 m) behind the firing line to 10 ft (3.0 m) into the tunnel. In addition to the wall treatments, which served to sufficiently reduce the peak pressures from the 20-mm guns to below 3 psi on any surface, a steel-framed muffler constructed of plywood and 12-in deep Rockwool insulation was built around and just forward of the 30-mm gun barrel. This further served to contain the muzzle blast.

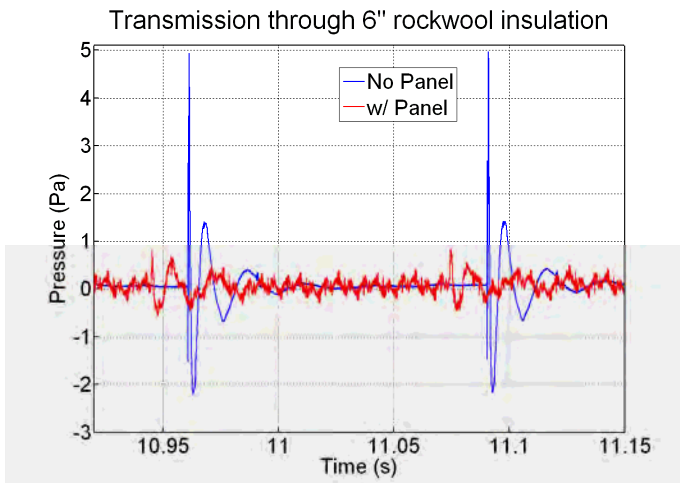

Figure 11: Measured transmission of a blast wave through an insulation panel.

C. Final Measurements

Final measurements on the completed room were performed in April 2009. Two 20-mm guns and the 30-mm gun were fired, and the data were recorded. The maximum pressure measured at the wall nearest to the 20-mm gun was 3100 Pa (0.45 psi). Since the 20-mm gun did not have a muffler in front of it, some of the pressures measured from it on the tunnel wall exceeded 1.5 psi but never more than 12400 Pa (1.8 psi). Table 1 gives a list of peak pressures at various locations inside the room. The highest pressures were actually caused mainly by the sonic booms from the rounds rather than the muzzle blasts.

Table 1: Peak pressures inside of the room during multi-round bursts. All pressures are given in Pa (psi).

Location	20-mm Gun	30-mm Gun
Side wall, near 20-mm gun	3100 (0.45)	1640 (0.24)
Tunnel wall, near ceiling	12400 (1.8)	5980 (0.87)
Tunnel ceiling, center	6490 (0.94)	10160 (1.47)
Front face, ceiling corner	3610 (0.52)	2750 (0.40)
Back platform	1910 (0.28)	2310 (0.36)

Air Force personnel also desired to know whether or not the machine shop could continue normal operation during firing. Microphones were placed at the entrance of the building and in the hallway to the machine shop, as those locations are where workers would be most exposed to noise. Exposure levels were calculated to determine the possible auditory risks. Peak pressure levels (dB re 20 μPa) and the 8-hour A-weighted equivalent noise levels (Leq_A) for a 50-round burst from the 30-mm gun are given in Table 2. Levels from jet aircraft flying overhead are also given for comparison. Noise levels from the gun were considered no more harmful than the general noise already present from machinery and aircraft.

Table 2: Peak pressure levels and equivalent noise levels for a 50-round burst.

Location	Peak pressure level (dB)	Leq_A (dBA)	Leq_A for jet flyover (dBA)
Outside, entrance	121.8	50.3	57.4
Inside, hallway	112.4	41.3	40.2

5. CONCLUSIONS

The goals of this project were to characterize the sound from the 30-mm GAU-8 Avenger, reduce the incident pressure on any surface inside the test range to less than 3 psi, and verify that exposure levels were safe for workers. From measurements taken at the UTTR, the muzzle blast was recorded and modeled using a rise time equation for weak shocks and the modified Friedlander wave equation. Measurements performed in the completed facility verify that the installed acoustical treatments attenuate the sound enough to fall below the 3-psi limit. Exposure levels for a 50-round burst were calculated for various locations outside the test facility and are safe for workers in the machine shop and around the test facility.

ACKNOWLEDGMENTS

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REFERENCES

[1] Mesa Corporation, *Final Report on 30mm Gun Functional Range Relocation to Hill Air Force Base* (Salt Lake City, Utah, May 24, 1985).

[2] Renkus-Heinz, Inc. http://www.rh.com/ease/index.html.

[3] Mark F. Hamilton and David T. Blackstock, eds., *Nonlinear Acoustics* (Acoustical Society of America, Melville, New York, 2008).

[4] Wilfred E. Baker, *Explosions in Air* (University of Texas Press, Austin, Texas, 1973).